

**Performance Assessment of the Eastern Range South Cape 915-MHz Doppler
Radar Wind Profiler**

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1. Introduction

The United States Space Force (USSF) is responsible for space vehicle launches at its Eastern Range (ER), which includes the Cape Canaveral Space Force Station (CCSFS). Multiple systems are used to measure the atmosphere at the ER, including suites of Doppler Radar Wind Profilers (DRWPs) operating at 915 MHz that measure winds within the lowest few kilometers of the atmosphere. Observations of boundary layer winds can be used for multiple applications, including serving as input to toxic dispersion models and characterizing winds for low-level aborts. The USSF upgraded the South Cape DRWP, which collected data during the fall of 2021. The USSF also requested NASA's Marshall Space Flight Center (MSFC) Natural Environments Branch (NE) to evaluate wind output from this DRWP system. This report describes the system and the analyses that MSFC NE conducted to demonstrate the system's wind accuracy relative to balloons from the Automated Meteorological Profiling System (AMPS), data availability, and effective vertical resolution (EVR).

2. Instrumentation Systems

The following subsections describe data from the different systems that were utilized during this study. The CCSFS Weather Station provided MSFC NE with ER balloon and DRWP data via a secured Aviation and Missile Research, Development, and Engineering Center data server. DRWP and balloon data were provided for the period of record (POR) dating from November 22, 2021 to November 29, 2021. Figure 1 displays the locations of the DRWP and the weather station.

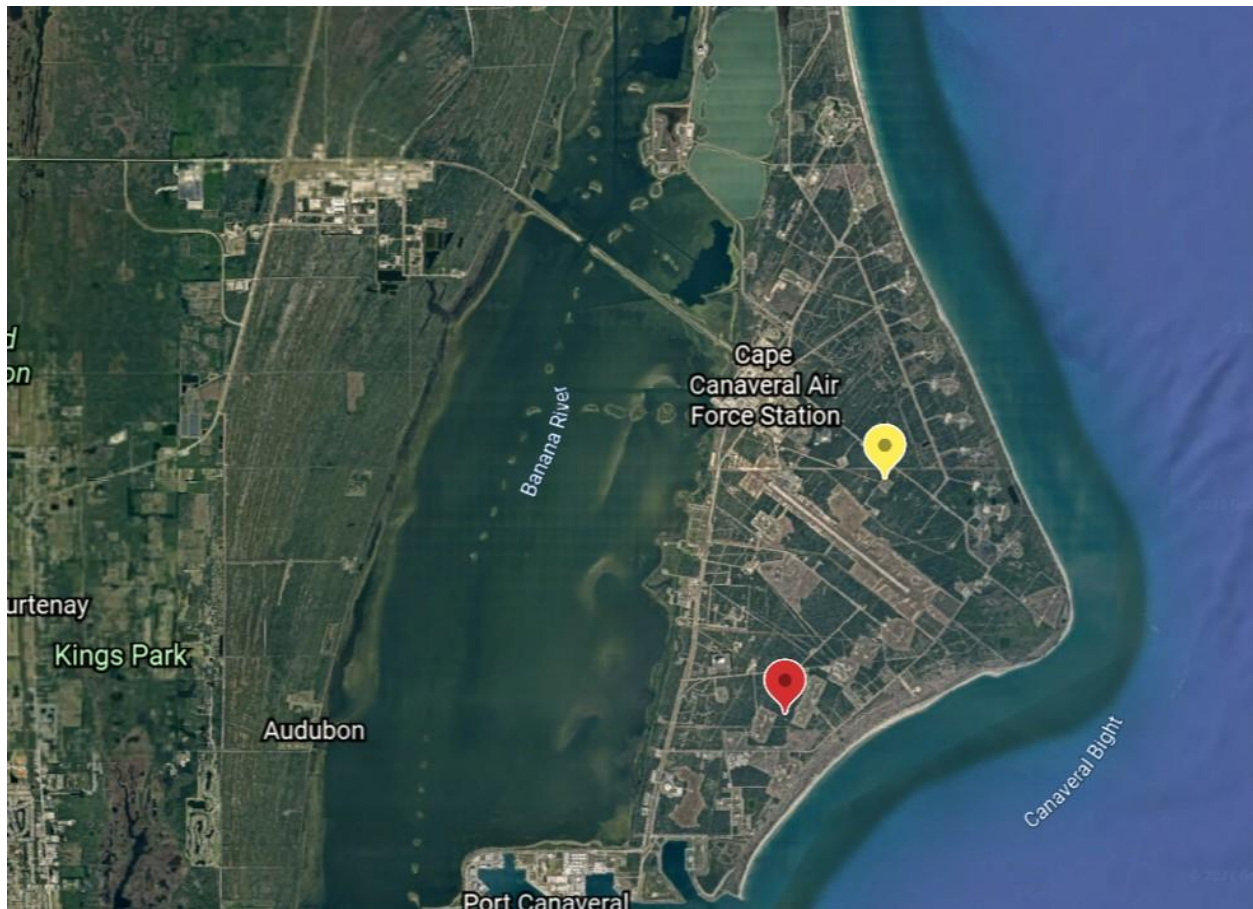


Figure 1: Locations of the CCSFS Weather Station and the South Cape DRWP, denoted by the yellow pin and red pin, respectively.

2.1.915-MHz DRWP

The DRWP derived boundary layer winds from 100 m to 5,000 m (328–16,404 ft) above ground level (AGL) in 100-m intervals. Although placeholders exist in the output data files for data records up to 5,000 m (16,404 ft), typical maximum altitudes were lower (see Section 3.2). The South Cape DRWP and weather station, from which the AMPS balloons are released, are located 4.41 km (2.74 mi) from each other. MSFC NE and the USSF agreed the optimal configuration would be for balloon releases and the DRWP be co-located. However, due to logistics, configuration, and time constraints, doing so was not feasible.

2.2. AMPS Balloons

The AMPS data used in this study were from balloons released during normal synoptic and launch operations during the POR. The AMPS archive included both Low Resolution Flight Element (LR) balloons and High Resolution Flight Element (HR) balloons released

during the POR. No balloons were released specific to this study. The LR balloons can reach over 30 km (19 mi) altitude while the HRs typically reach approximately 16–18 km (10–11 mi) altitude. Both LR and HRs report data in one-second intervals, and MSFC NE generated text files from the binary .w9k files using the Win9000 processing software (Lockheed Martin, 2013). Variables extracted for this analysis consisted of launch date, as well as time, latitude, longitude, geometric height above mean sea level (MSL), wind speed, and wind direction at each one-second interval.

3. Analyses

This section describes the methodology and results of the three analyses that MSFC NE conducted to evaluate the DRWP. The first analysis entailed comparing DRWP wind profiles to concurrent AMPS balloon measurements to quantify the differences between the two systems. The second analysis consisted of assessing data availability versus altitude, which quantifies how often one should expect to obtain complete profiles to an altitude of interest. The third analysis comprised of examining the EVR of the DRWP, which quantifies the granularity of the wind features that the system resolves. Each subsection presents the analysis methodology and discusses results.

3.1. Comparison of Wind Profiles to Concurrent Balloon Measurements

MSFC NE compared wind profiles from the DRWP to concurrent wind profiles from the AMPS balloon. For this analysis, both LR and HR balloons were used. Balloon profiles were vertically matched to the 915-MHz DRWP profiles by block averaging the balloon westerly (U) and southerly (V) wind components in 100-m (328 ft) intervals. Additionally, DRWP altitudes were adjusted from height AGL to height above MSL for this analysis. To be compared to a balloon, the DRWP profile had to exist within ± 7.5 minutes of the first balloon observation. This procedure was performed without implementing any quality control.

Plots in this section show the sample size and statistical quantities of the differences between concurrent DRWP and balloon wind components, vector wind magnitude, and wind direction versus altitude (AGL). First, wind component deltas were generated as

$$\Delta U = U_{DRWP} - U_{Balloon}, \text{ and} \quad (1a)$$

$$\Delta V = V_{DRWP} - V_{Balloon} \quad (1b)$$

where subscripts “DRWP” and “Balloon” denote the source of the respective wind component. Next, the vector wind magnitude delta, $\Delta \vec{V}$, was computed as

$$\Delta \vec{V} = \sqrt{\Delta U^2 + \Delta V^2}. \quad (2)$$

Last, the wind direction delta, $\Delta\theta$, was computed as the smallest angle between the concurrent DRWP and balloon wind vectors. The cosine of this quantity is defined as the vectors' dot product divided by the product of their magnitudes, which equates to

$$\Delta\theta = \cos^{-1} \left(\frac{U_{DRWP} * U_{Balloon} + V_{DRWP} * V_{Balloon}}{WS_{DRWP} * WS_{Balloon}} \right) \quad (3)$$

where WS_{DRWP} and $WS_{Balloon}$ denote the wind speed from the DRWP and balloon, respectively. Note that $WS_{Balloon}$ was computed as the root-sum-square of the block-averaged balloon wind components.

MSFC NE computed these quantities to statistically characterize the differences between balloon and DRWP observations, and thus quantify the error of the DRWP relative to balloon measurements. It is important to note that deltas from concurrent balloon measurements do not equate to the absolute error of the DRWP for two reasons. First, balloon observations contain their own measurement error. Second, valid measurements from multiple systems sampling different wind regimes (driven by the spatial separation between concurrent DRWP and balloon measurements) contribute to the calculated differences. No attempt was made to account for this attribute, but MSFC NE let it be known that that the separation between the balloon release point and the DRWP would impact this assessment. The USSF then agreed that results would represent an upper bound on DRWP measurement error. Sample size restrictions were implemented to ensure that statistical quantities were generated from a reasonable number of comparisons. At each altitude, the mean, root-mean-square (RMS), and 99% envelope were initially computed. Then, the mean, RMS, and 99% envelope were retained from at least 10, 30, and 100 comparisons, respectively. For reference, Pinter et al. (2004) found a mean difference of 0.85 m/s (2.79 ft/s) and an RMS difference of 1.51 m/s (4.95 ft/s) between 1 km (0.6 mi) and 9 km (6 mi) for pairs of simultaneously-released HR balloons.

Of the 26 AMPS balloon profiles provided, 16 profiles were used to compute statistical quantities of wind component, vector wind magnitude, and wind direction deltas between concurrent DRWP and balloon measurements. Additionally, sample size versus altitude varied because the DRWP did not contain data at all altitudes. Typically, the number of reports decreased with altitude due to weaker return signal. Figure 2 displays the number of concurrent DRWP and balloon records available for comparison at each altitude. The figure shows that at most 16 comparisons were given to compute statistics at any given altitude. Therefore, RMS and 99% deltas were not retained for this study.

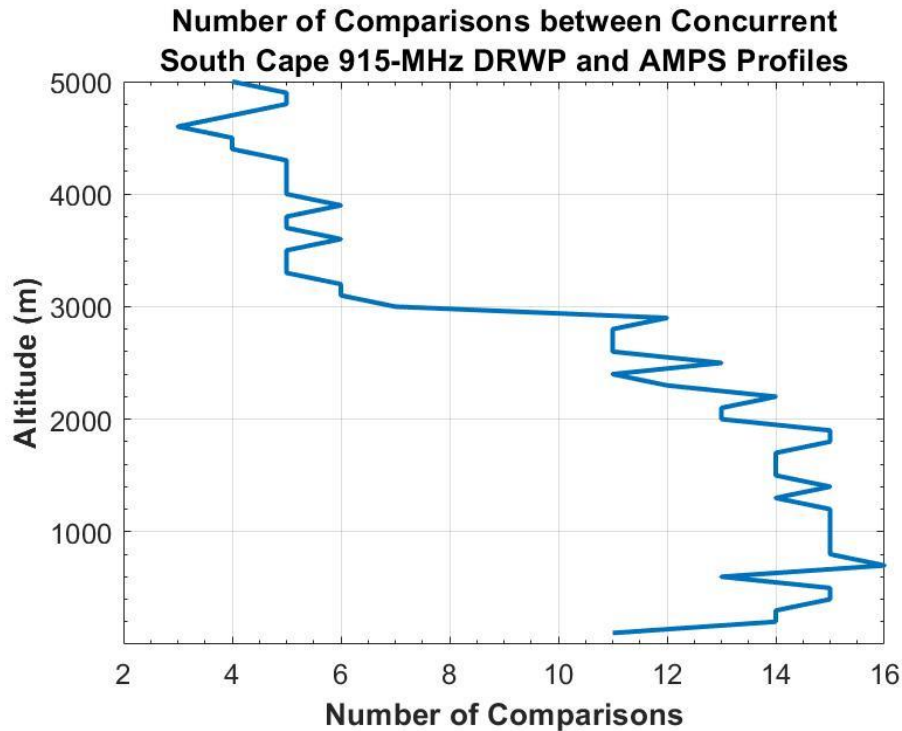


Figure 2: Number of comparisons to concurrent balloon data versus altitude (AGL) for the South Cape 915-MHz DRWP.

The mean deltas of each quantity, shown in Figure 3, provide an estimate of bias of the DRWP (relative to balloon measurements). The left panel displays the mean wind component deltas. The mean ΔU stayed between 0–0.7 m/s (0–2.3 ft/s) from 100 m (328 ft) to 1,000 m (3,281 ft), right around 0 m/s (0 ft/s) from 1,100 m (3,609 ft) to 2,300 m (7,546 ft) and fluctuated between -1–0.7 m/s (-3–2.3 ft) from 2,400 m (7,874 ft) to 2,900 m (9,514 ft). The mean ΔV remained between 0–0.3 m/s (0–1.0 ft/s) from 100 m (328 ft) to 500 m (1,640 ft), between -0.5–0 m/s (-1.6–0 ft/s) from 500 m (1,640 ft) to 1,200 m (3,937 ft), and between 0–1.2 m/s (0–3.9 ft/s) from 1,200 m (3,937 ft) to 2,900 m (9,514 ft). No values are shown above 2,900 m (9,514 ft) because there were fewer than 10 comparisons at those altitudes. The center panel shows the mean vector delta. This quantity stayed between 1.2–1.6 m/s (3.9–5.2 ft/s) from 100 m (328 ft) to 1,500 m (4,921 ft) and between 1.6–2.3 m/s (5.2–7.5 ft/s) from 1,600 m (5,249 ft) to 2,900 m (9,514 ft). The right panel presents the mean $\Delta\theta$ versus altitude, which from 100 m (328 ft) to 900 m (2,953 ft) is around 5°–10° and increases to 20° at 1,100 m (3,609 ft) and 22° at 1,400 m (4,593 ft). From 1,500 m (4,921 ft) to 2,900 m (9,514 ft) the mean $\Delta\theta$ is between 5°–18°. This analysis of $\Delta\theta$ was performed ignoring the relationship between wind direction and wind speed.

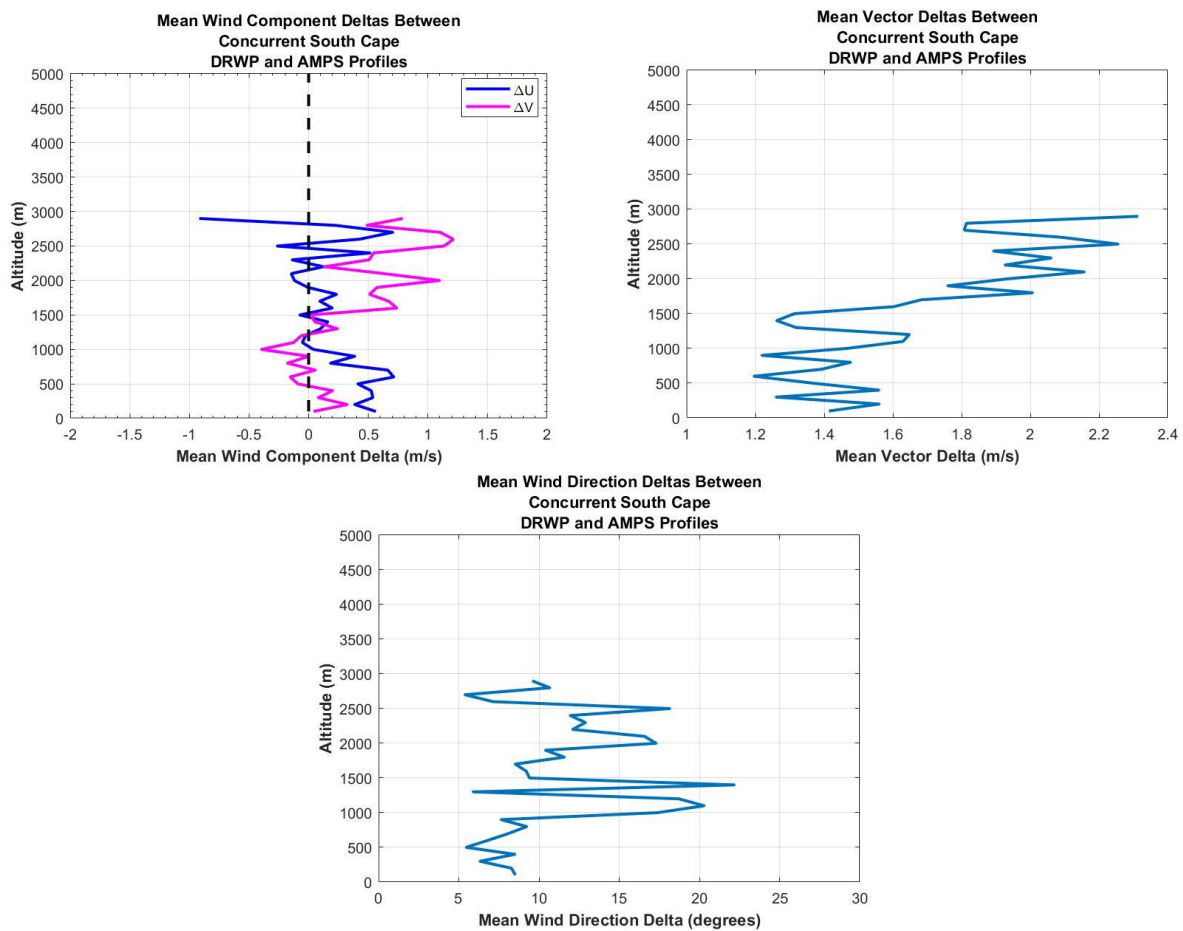


Figure 3: Mean deltas of wind components (m/s, left), vector magnitude (m/s, center), and wind direction (degrees, right) versus altitude (AGL) between concurrent data from the South Cape 915-MHz DRWP and balloon data.

3.2. Data Availability

An analysis of data availability versus altitude was conducted for the DRWP to show the probability of receiving vertically complete profiles within a specified altitude range. For this analysis, data availability was defined as 100% times the ratio of the number of profiles that contained data at all altitudes between the bottom of the profile and a given altitude to the total number of profiles collected. A profile was collected at 99.7% of the total number of 15-minute timestamps in the POR.

Figure 4 shows the probability of a profile extending without gaps from the bottom altitude of 100 m (328 ft) to the selected altitude on the ordinate. Data availability at 100 m (328 ft) was near 64%, and the percent of available profiles decreased with increasing altitude

range. One should interpret this figure as the percent of complete profiles from 100 m to the altitude specified on the ordinate, given that a profile existed. For example, 30% of the DRWP profiles were complete from 100–1,500 m (328–4,921 ft).

Additional examination of data availability versus altitude was also performed. Figure 5 displays the percent of valid data records at discrete altitudes and shows that data availability increased from 64% at 100 m (328 ft) to 96% at 800 m (2,625 ft). Thus, Figure 6 was created to show the percent of complete profiles extending from 200 m (656 ft) to specified altitudes. Results display a similar trend to Figure 4, with 90% of the profiles complete at 200 m (656 ft), dropping to less than 10% of the profiles by 3,000 m (9,843 ft).

The percent data availability at discrete altitudes (Figure 5) also provides insight to any applications that do not require complete profiles, such as assessments at discrete altitudes or within specified altitude ranges. Most valid records existed from 200–2,000 m (656–6,562 ft), with a gradual decrease in the percent available data records to roughly 70% at 5,000 m (16,404 ft).

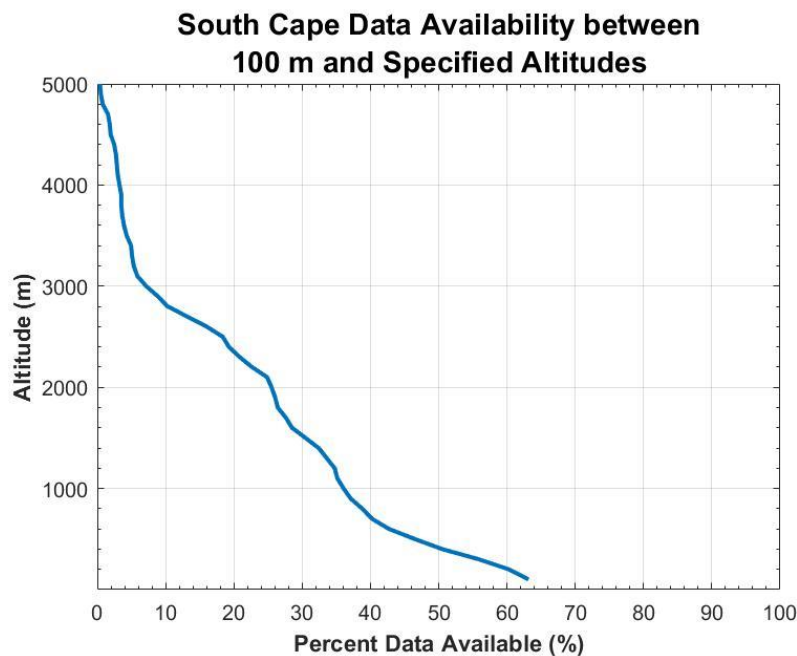


Figure 4: Percent of profiles containing no missing data from 100 m (328 ft) to the altitude specified on the ordinate.

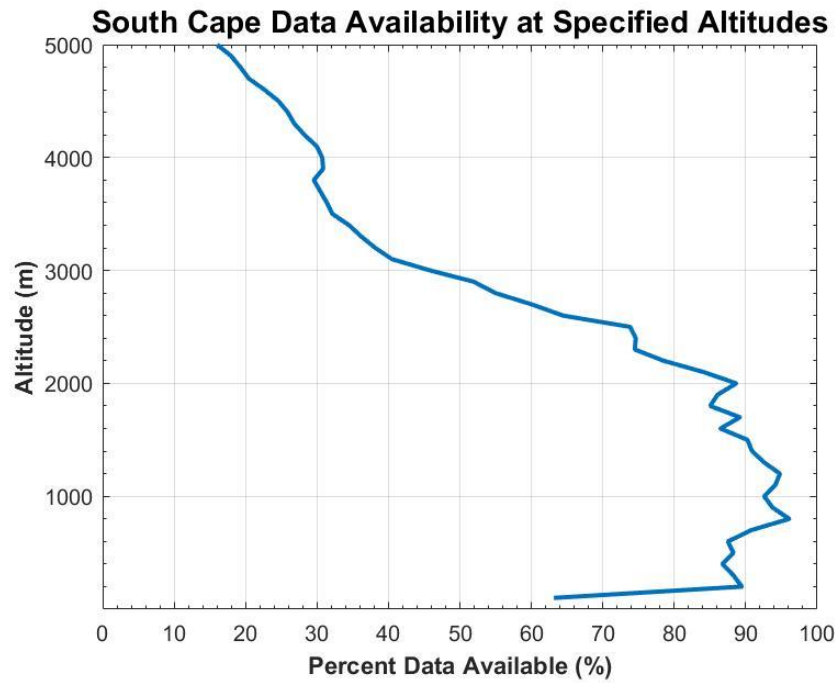


Figure 5: Percent of the DRWP archive that contains data records at discrete altitudes.

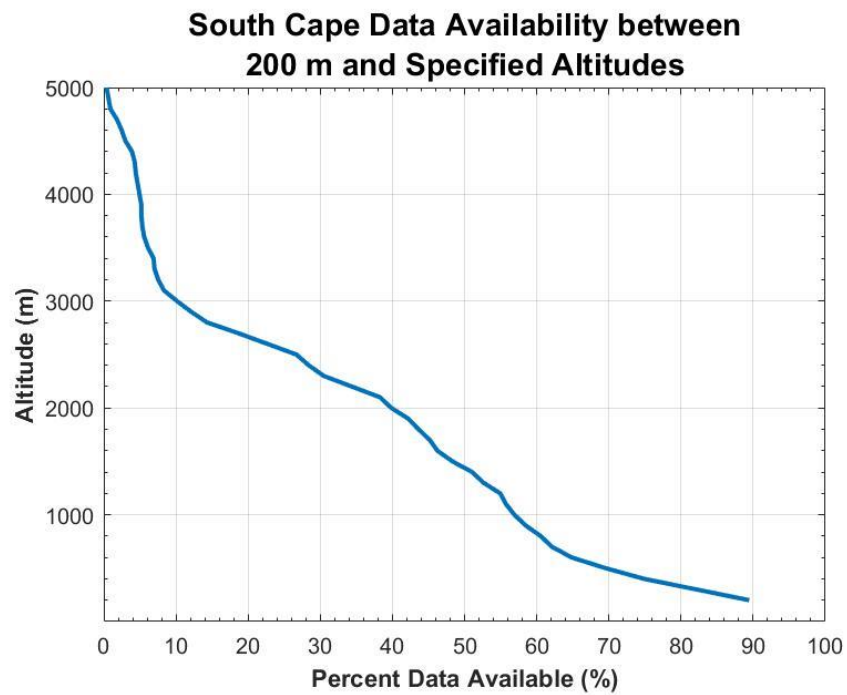


Figure 6: Percent of profiles containing no missing data from 200 m (656 ft) to the altitude specified on the ordinate.

3.3. Effective Vertical Resolution

Analyses of mean power spectral density (PSD) were conducted to estimate the EVR of the DRWP. First, complete wind component profiles between two specified altitude ranges were extracted. Profiles from 200-4,700 m (656-15,420 ft) correspond to the maximum altitude range of the system and profiles from 200-3,000 m (656-9,843 ft) envelope the altitude range needed to combine data with the Tropospheric Doppler Radar Wind Profiler. The lower bound of 200 m (656 ft) was chosen to mitigate any effects due to the relatively low data availability described in Section 3.2, and no complete profiles from 200 m (656 ft) to a higher altitude were present. This segregation resulted in 14 complete profiles from 200-4,700 m (656-15,420 ft), with 46 points per profile, and 78 complete profiles from 200-3,000 m (656-9,843 ft), with 29 points per profile. Next, the mean and linear trend were removed from each wind component profile and a Hanning window with zero overlap was applied to the profile. Then, the Fast Fourier Transform of each profile was computed and used to generate each profile's PSD. Last, mean PSD at each wavelength was computed and displayed on a log-log plot as a function of wavelength. Results are shown in Figure 7, which also includes a reference line derived from the linear fit to the linear portion of the mean U component PSD (in log space).

The EVR was estimated by determining the wavelength at which the PSD begins to deviate from a linear trend when reading the plot from right-to-left. No such deviation was evident in results from examining profiles from 200-4,700 m (656-15,240 ft), and the PSDs of profiles from 200-3,000 m (656-9,843 ft) were found to be quasi-parallel to the reference line down to roughly 250-300 m (820-984 ft). However, a precise boundary wavelength could not be determined, which is surmised to be due to the small sample of the profiles available. Iterations of this analysis performed using a Parzen window and various other altitude ranges produced similar results that are not shown here. Thus, this study does not report an estimate of EVR of the South Cape DRWP. For reference, recent studies of the same 915-MHz DRWP systems at Titusville-Cocoa and False Cape (MSFC NE 2021) estimate the EVR to be 250 m (820 ft), and Wilfong (2017) found the EVR of AMPS one-second HR and LR profiles to approximate 160 m and 270 m, respectively.

This study did not utilize coherence to determine EVR. The coherence analysis relies on an assumption that the profiles in the pair used represent a static atmosphere. Results from studies of other recently upgraded DRWPs showed extremely large boundary wavelengths and did not align with the spectral signatures shown in the PSDs. It was determined that the discrepant results in the coherence analysis stemmed from the time separation of 15 minutes between temporally adjacent profiles not meeting the assumption that the atmosphere remains static over the sampling period.

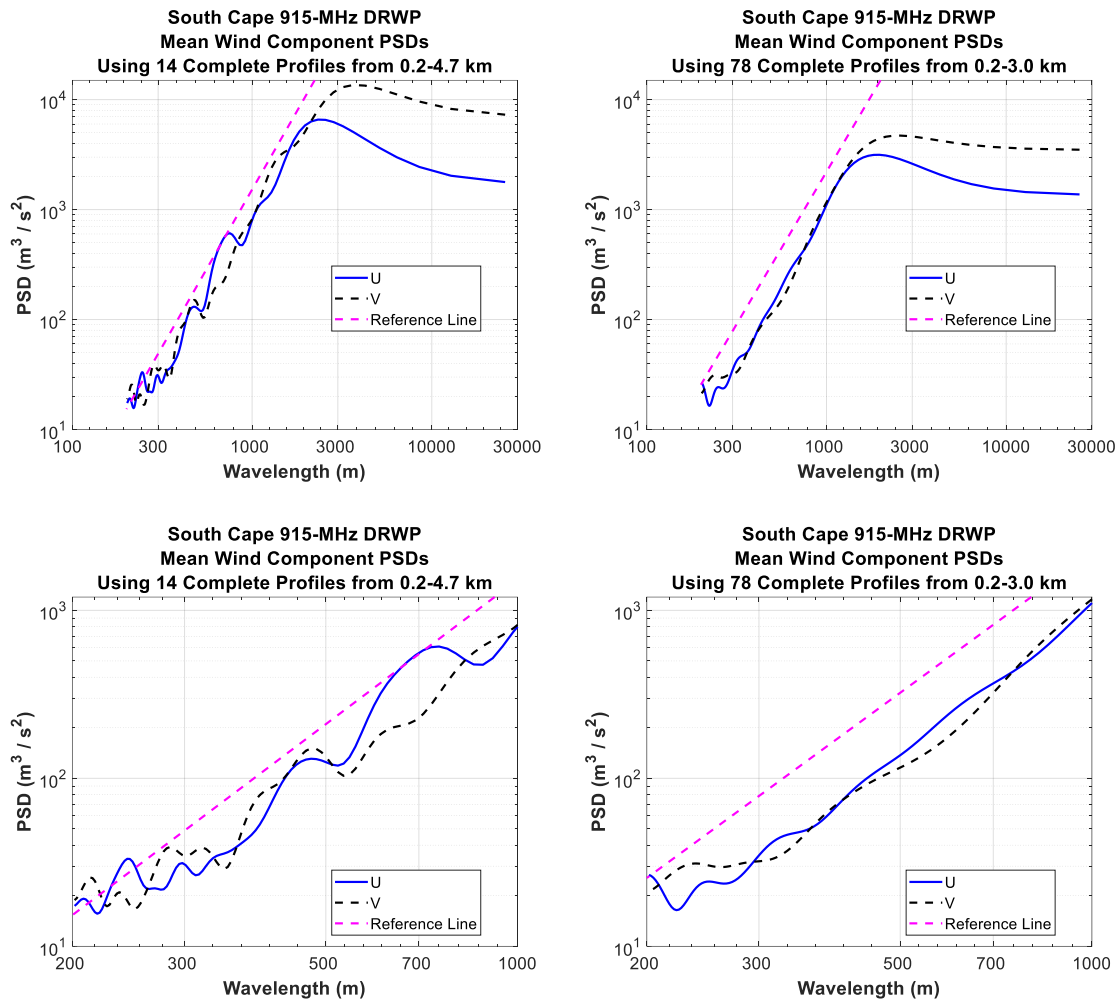


Figure 7: Mean PSDs (m^3s^{-2}) versus wavelength (m) using complete DRWP profiles from 200-4,700 m (656-15,420 ft) altitude (left) and 200-3,000 m (656-9,843 ft) altitude (right) at all wavelengths (top) and from 200-1,000 m (656-3,281 ft) wavelength (bottom). Blue, solid lines and dashed, black lines denote the PSD for U and V, respectively. The dashed, magenta line shows a linear approximation for reference.

4. Summary

This report documents analyses conducted to evaluate wind profile output from the South Cape 915-MHz DRWP using wind profile measurements from November 22, 2021 to November 29, 2021. Analyses included comparing wind components from the DRWP to concurrent AMPS balloon wind profiles, examining the percent of complete profiles, and attempting to quantify the DRWP's EVR. The left panel displays the mean wind component deltas. The mean ΔU stayed between -1.0–0.7 m/s (-3.3–2.3 ft/s) from 100 m (328 ft) to 2,900 m (9,514 ft). The mean ΔV remained between -0.5–1.2 m/s (-1.6–3.9 ft/s) from 100 m (328 ft) to 2,900 m (9,514 ft). The mean vector delta stayed between 1.2–

2.3 m/s (3.9–7.5 ft/s) from 100 m (328 ft) to 2,900 m (9,514 ft). The mean $\Delta\theta$ versus altitude was between 5°–22° from 100 m (328 ft) to 2,900 m (9,514 ft).

The percent of available profiles from the DRWP tended to decrease with increasing altitude and showed a slight sensitivity to the minimum altitude selected. Data availability at 100 m (328 ft) was found to be 64%, but data availability at 800 m (2,624.7 ft) was approximately 96%.

The DRWP EVR was not quantified, as the PSDs did not show a distinct noise floor. However, in general, results were consistent with recent studies of the same DRWP systems at other ER locations, which estimated an EVR of 250 m (820 ft). It is surmised that more data are needed to confirm the same EVR for the South Cape DRWP. One should note that the DRWP produces wind profiles more frequently than typical balloon releases, but DRWP profiles tend to have a smaller vertical domain and a larger sampling interval.

4. Acknowledgements

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